METHOD AND APPARATUS FOR IRRADIATING A TARGET

FIELD OF THE INVENTION

[0001] The present invention relates, in general, to irradiating a target and, more particularly, to adjusting a radiation beam to track the motion of the target.

BACKGROUND OF THE INVENTION

[0002] Radiation therapy is widely used for the treatment of tumors. A course of radiation therapy typically includes a planning session and one or more treatment sessions. During the planning session, an oncologist obtains information describing the nature, location, size, and shape of the tumor. Based on the information, the oncologist develops a treatment plan that includes such parameters as radiation beam energy, radiation dose, treatment duration, etc. The treatment plan is executed during the treatment sessions.

[0003] In an intensity modulated radiation therapy (IMRT), the radiation intensity projected onto different parts of the tumor can be adjusted according to the treatment plan. The intensity modulation enables the oncologist to adjust the radiation dose received by different parts of the patient's body. Using IMRT, the oncologist can deliver a high radiation dose to the tumor, thereby increasing the therapy efficiency and reducing the inadvertent radiation exposure of the healthy tissues surrounding the tumor.

[0004] During a treatment session, the tumor may move due to the breathing or gastric and intestinal movements of the patient. Breathing motion momentarily and repeatedly causes the tumor to move out of the radiation beam and subjects the healthy tissues surrounding the tumor to the radiation. Training the patient for proper breathing techniques may reduce, but not eliminate, the movement of some tumors. The physiological gating of the radiation beam during the treatment session may also reduce the radiation exposure of the healthy tissues by switching off the radiation beam when the tumor moves out of the projected area of the radiation beam. In one gating process, the movement of the tumor is approximated as sinusoidal with a frequency equal to the inhale/exhale frequency of the patient. In another gating process, markers are placed on patient's thorax and/or abdomen to facilitate the detection of patient breathing and/or gastric and intestinal movements. Although the physiological gating process can reduce the radiation exposure of the tissues surrounding the tumor, it may prolong the duration of the treatment session by periodically switching off the radiation beam. This may reduce the throughput of the radiation therapy.

[0005] Accordingly, it would be advantageous to have an apparatus and a method for tracking the tumor movement during a radiation treatment therapy. It would also be advantageous for the apparatus and the method to be able to adjust the radiation beam in response to the tumor movement. It would be of further advantage if the apparatus can be made by modifying an existing radiation therapy apparatus.

SUMMARY OF THE INVENTION

[0006] In one aspect, the present invention provides an apparatus and a method for irradiating a target. In a specific aspect, the present invention provides an apparatus and a process for detecting a movement of the target and dynamically adjusting a radiation beam to track the target.

[0007] In accordance with one embodiment of the present invention, an apparatus for irradiating a target includes a radiation source that generates a radiation beam, e.g., a cone shaped radiation beam, and a beam adjuster, e.g., a multiple leaf collimator, for collimating and adjusting the shape of the radiation beam from the radiation source that would be projected onto the target. An image detector detects the image beam and generates an image signal of the target. The target signal is used to generate a beam adjustment signal for controlling the beam adjuster, thereby enabling the radiation beam generated by the radiation source to track the target.

[0008] In accordance with a specific embodiment of the present invention, the apparatus and the method are used for radiation treatment of tumors. Fiducial markers may be coupled to the target, i.e., the tumor under the radiation treatment. The fiducial markers form a sharp image on the image detector when illuminated by an image beam, e.g., a low energy X-ray beam, thereby indicating the location, orientation, shape, and/or size of the tumor to be treated under the radiation therapy.

[0009] In accordance with another specific embodiment of the present invention, a radiation treatment apparatus includes a radiation source that generates a radiation beam and a beam adjuster, e.g., a multiple leaf collimator, for collimating and adjusting the shape of the radiation beam from the

radiation source that would be projected onto the patient. An image detector, e.g., a video camera, detects the images of an external marker placed on the thorax and/or abdomen of the patient and generates an image signal of the external marker. Using a previously established relationship between the tumor movement and the marker positions, a beam adjustment signal for controlling the beam adjuster is generated in response to the image signal of the external markers, thereby enabling the radiation beam to track the tumor.

[0010] In accordance with various alternative embodiments of the present invention, the radiation beam can track the target by moving a gantry on which the radiation source is mounted, by moving a platform on which the target is placed. Tracking through the beam adjuster as described herein above can be used in any combination with these and other processes. In addition, a process of irradiating a target can also incorporate a gating process that temporarily switches off the radiation source in response to a sudden target movement.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Figure 1 is a functional block diagram illustrating a radiation apparatus in accordance with the present invention;

[0012] Figure 2 illustrates a radiation apparatus in accordance with an embodiment of the present invention;

[0013] Figure 3 illustrates a radiation apparatus in accordance with another embodiments of the present invention;

[0014] Figure 4 illustrate a multiple leaf collimator in accordance with an embodiment of the present invention; and

[0015] Figure 5 is a flowchart illustrating a radiation therapy process in accordance with the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0016] Preferred embodiments of the present invention are described hereinafter with reference to the figures. It should be noted that the figures are not drawn to scale and elements of similar structures or functions are represented by like reference numerals throughout the figures. It should also be noted that the figures are only intended to facilitate the description of specific embodiments of the invention. They are not intended as an exhaustive description of the invention or as a limitation on the scope of the invention. In addition, an aspect described in conjunction with a particular embodiment of the present invention is not necessarily limited to that embodiment and can be practiced in any other embodiments of the present invention.

[0017] Figure 1 is a functional block diagram illustrating a radiation therapy apparatus 10 in accordance with the present invention. Apparatus 10 includes a radiation source 12. By way of example, radiation source 12 generates X-ray radiation at a mega-volt (MV) energy spectrum in a radiation beam 15 toward a platform or a couch 14. A beam adjuster 16 is located between radiation source 12 and couch 14 and functions to adjust the shape, size, and direction of a radiation beam 19 reaching a patient 100 on couch 14 during a radiation treatment session. Apparatus 10 also includes a control module 18 coupled to radiation source 12, couch 14, and beam adjuster 16 to control their operations. In addition, apparatus 10 includes an image beam source 11 and an image detector 17 coupled to control module 18. By way of example, image beam source 11 generates a low energy X-ray beam 13 at a

kilo-volt (kV) level, and image detector 17 is an X-ray image detector.

[0018] In accordance with one embodiment of the present invention, control module 18 includes a signal processor such as, for example, a digital signal processor (DSP), a central processing unit (CPU), or a microprocessor (μP), and a memory coupled to the signal processor. The memory serves to store a treatment plan for patient 100 and other programs for the operation of apparatus 10. The signal processor executes the programs and generates signals for the operation of radiation source 12, couch 14, beam adjuster 16, image beam source 11, and image detector 17. The signal processor also receives image signals from image detector 17 and generates tracking signals in response to thereto.

[0019] It should be noted that apparatus 10 in accordance with the present invention is not limited to having the structure as describe herein above. For example, radiation source 12 is not limited to generating X-ray radiation beam 15 at the MV energy spectrum. Depending on the nature of treatment or application, radiation source 12 may generate X-ray radiation at other energy spectrums or generate other kinds of radiation beams, which include, but are not limited to, beta ray beams, positron beams, proton beams, antiproton beams, neutron beams, heavy ion beams, e.g., alpha ray beams, carbon ion beams, etc. Likewise, image beam source 11 is not limited to generating X-ray radiation beam 13 in the kV energy spectrum. Further, apparatus 10 is not limited to having one image beam source 11 and one image detector 17 as shown in Fig. 1. In alternative embodiments, apparatus 10 may include two or more image beam sources and two or more image detectors. For example, a

plurality of image beam sources and image detectors are generally required for providing stereotaxic data.

[0020] In accordance with an alternative embodiment of the present invention, apparatus 10 does not include image beam source 11. Image detector 17 in apparatus 10 includes one or more video cameras for generating images signals regarding the external anatomy of patient 100. In accordance with another alternative embodiment, image detector 17 includes a magnetic field detector for generating image signals by detecting one or more magnetic markers or seeds implanted in patient 100.

[0021] Figure 2 is a schematic diagram illustrating a radiation therapy apparatus 20 in accordance with an embodiment of the present invention. The functional structure of apparatus 20 is similar to that of apparatus 10 described herein above with reference to Fig. 1. Apparatus 20 includes a gantry 25 positioned over platform or couch 14 and housing radiation source 12 and beam adjuster 16. In a preferred embodiment, gantry 25 is capable of rotating around couch 14 so that the radiation beam generated by radiation source 12 can be projected onto a patient on couch 14 at different angles. Apparatus 20 also includes two image beam sources, 11A and 11B, mechanically coupled to the opposite sides of gantry 25. Two image detectors, 17A and 17B, are also mechanically coupled to gantry 25 (not shown in Fig. 2). Preferably, the positions and orientations of image beam sources 11A and 11B and image detectors 17A and 17B are adjustable to accommodate different patients. A control module 18 controls the operation of apparatus 20.

[0022] In operation, control module 18 processes the image signals from image detectors 17A and 17B to calculate the data

regarding the position, shape, and/or size of the tumor in the patient. These data are used to generate beam adjustment signals to control beam adjuster 16, thereby adjusting the position of the radiation beam projected on the patient. In alternative embodiments, the beam adjustment signals can also control gantry 25 for changing beam position and/or control couch 14 for repositioning the patient. In general, any combination of the movements of beam adjuster 16, gantry 25, and couch 14 may be used to cause the position of the radiation beam to track the movement of target. Accordingly, discussion of any mode of target tracking herein does not preclude use of other modes in addition to the mode under discussion. The control signal can additionally be used for switching the radiation beam on and off in a gating process, as will be described in more detail below.

[0023] Apparatus 20 is not limited to having two image beam source, 11A and 11B, and two image detectors, 17A and 17B, as shown in Fig. 2. Depending on the desired accuracy of the tumor movement tracking, apparatus 20 can have only one image beam source and one image detector, or have more than two image beam sources and more than two image detectors. Furthermore, image beam sources 11A and 11B and image detectors 17A and 17B are not limited to being mechanically coupled to gantry 25. In an alternative embodiment, image beam sources 11A and 11B are mounted on the ceiling of a treatment room, in which apparatus 20 is installed. Likewise, image detectors 17A and 17B can be mounted on couch 14 or in the floor of the treatment room.

[0024] In accordance an alternative embodiment of the present invention, the radiation beam generated by radiation source 12

serves as both a radiation treatment beam and an image forming beam. Apparatus 20 includes an image detector (not shown in Fig. 2) for detecting the images of the target or fiducial markers on the patient formed by the radiation beam generated by radiation source 12. In a typical radiation treatment therapy, the radiation beam generated by radiation source 12 is a high energy X-ray beam at an MV energy spectrum. On the other hand, the image beam generated by image beam source 11A or 11B typically has a kV energy spectrum. A system using X-ray radiation at different energy spectrums for imaging is described in U.S. Patent Application Serial No. __/______ (Attorney Docket No. 05513.P003) entitled "RADIOTHERAPY APPARATUS EQUIPPED WITH AN ARTICULABLE GANTRY FOR POSITIONING AN IMAGING UNIT" and filed on November 2, 2001 and U.S. Patent Application Serial No. __/______ (Attorney Docket No. 261/132) entitled "X-RAY IMAGE ACQUISITION APPARATUS" and filed on November 2, 2001, which are incorporated herein by reference in their entireties.

[0025] Figure 3 is a schematic diagram illustrating a radiation therapy apparatus 30 in accordance with another embodiment of the present invention. Like apparatus 20 shown in Fig. 2, apparatus 30 includes gantry 25 positioned over platform or couch 14 and housing radiation source 12 and beam adjuster 16. In a preferred embodiment, gantry 25 is capable of rotating around couch 14 so that the radiation beam generated by radiation source 12 can be projected onto a patient on couch 14 at different angles. Apparatus 30 is used in conjunction with an image detector 17, which is, by way of example, a video camera. Typically, video camera 17 is room mounted. Preferably, the position and orientation of video

camera image detector 17 are adjustable to accommodate different patients under treatment.

[0026] In operation, video camera image detector 17 generates image signals regarding the external anatomy of the patient, or one or more external markers placed on the patient. Control module 18 processes the image signals from video camera image detector 17 to deduce the data regarding the position, shape, and/or size of the tumor using an established relationship between the tumor position, shape and/or size and the external anatomy of the patient or the marker. These data are used to generate beam adjustment signals to control beam adjuster 16, thereby adjusting the position of the radiation beam projected on the patient. In alternative embodiments of the present invention, the beam adjustment signals can also control radiation source 12 for gating, control gantry 25 for changing beam direction, and/or control couch 14 for repositioning the patient.

[0027] Apparatus 30 is not limited to having one video camera image detector 17 as shown in Fig. 3. Depending on the desired accuracy of the tumor movement tracking, apparatus 30 can have more than one image detectors for stereotaxic information of the patient's anatomy. Further, apparatus 30 can also include image beam sources and corresponding image detectors like those shown in Fig. 2, thereby enabling apparatus 30 to generate both external and internal anatomical or marker data of the patient. In addition, apparatus 30 can include magnetic field detectors to detect the magnetic field of magnetic seeds implanted in the patient.

[0028] Figure 4 is a schematic diagram illustrating a multiple leaf collimator 40 that can function as beam adjuster 16 shown

in Figs. 1, 2, and 3 in accordance with an embodiment of the present invention. Multiple leaf collimator (MLC) 40 includes a first row 41 of multiple leaves 41A, 41B, …, and 41N, and a second row 42 of multiple leaves 42A, 42B, …, and 42N. Multiple leaves 41A-41N in row 41 are parallel to each other. Likewise, multiple leaves 42A-42N in row 42 are parallel to each other. Further, row 41 of leaves 41A-41N and row 42 of leaves 42A-42N are opposite to each other. Each of multiple leaves 41A-41N in row 41 and each of multiple leaves 42A-42N in row 42 is individually movable in a direction indicated by a double ended arrow 45 in Fig. 4. Leaves 41A-41N and 42A-42N in MLC 40 are preferably made of such a material that enable them to effectively block the radiation generated by radiation source 12. Materials typically suitable for leaves 41A-41N and 42A-42N in MLC 40 include tungsten, tantalum, lead, etc.

[0029] In operation, a control module, e.g., control module 18 shown in diagram Figs. 1, 2, and 3, controls the motion of multiple leaves 41A-41N and 42A-42N to shape the radiation beam generated by radiation source 12. The radiation beam shaped by MLC 40 preferably irradiates the tumor in a patient on couch 14 with minimum radiation exposure on the healthy tissues surrounding the tumor. In one embodiment, control module 18 adjusts MLC 40 to shape the radiation beam to be conformal to the tumor in the patient. In another embodiment, control module 18 adjusts MLC 40 to both shape the radiation beam to be conformal to the tumor and modulate the intensity of the radiation beam projected on the patient.

[0030] The number of leaves 41A-41N and 42A-42N in MLC 40 can have a wide range. Generally, an MLC having a large number of narrow leaves has a higher resolution than an MLC having a

small number of thick leaves. A high resolution is generally beneficial in shaping the radiation beam precisely to the shape of the tumor and modulating the radiation intensity precisely. In one example, each of rows 41 and 42 in MLC 40 includes forty leaves. In another example, each of rows 41 and 42 in MLC 40 includes 75 leaves.

[0031] Multiple movable leaves 41A-41N and 42A-42N in MLC 40 are not limited to being straight and parallel to each other as shown in Fig. 4. They can be curved or bent. Certain shapes and arrangements for leaves 41A-41N and 42A-42N may benefit the manufacturing, operation, and/or maintenance of MLC 40. These and other design variations for MLC 40 are within the scope of the present invention.

[0032] In an alternative embodiment of the present invention, beam adjuster 16 includes two multiple leaf collimator, each like MLC 40 shown in Fig. 4, with one collimator stacked over the other collimator. The multiple leaves in one MLC are at an angle, e.g., 90 degrees (°), with respect to the multiple leaves in the other MLC. Such an arrangement of two MLCs stacked over each other is also referred to as a biplanar multiple leaf collimator. Beam adjuster 16 including two MLCs arranged as a biplanar MLC is capable of shaping the radiation beam in more diverse shapes than that including only one MLC. It should be noted that the angle between the leaves of the two MLCs in a biplanar MLC is not limited to being 90°. In accordance with the present invention, the leaves in the two MLCs are preferably not parallel to each other, thereby rendering beam adjuster 16 higher degrees of freedom in adjusting shape of the radiation beam than a beam adjuster with only one MLC.

[0033] Figure 5 is a flowchart schematically illustrating a radiation therapy process 50 in accordance with a specific embodiment of the present invention. By way of example, radiation treatment process 50 can be performed using apparatus 10, 20, and 30 described herein above with reference to Figs. 1, 2, and 3, respectively.

[0034] In a planning step 51, a treatment plan for a patient is established based on the nature, size, shape, and location of the tumor in the patient. In accordance with one embodiment of the present invention, the treatment plan preferably includes data regarding the radiation doses different portions of the tumor should receive. Typically, the treatment plan will set forth several treatment sessions, which are also referred to as fractions. During each fraction, the patient may receive radiation from several angles. Each such angle for receiving radiation is referred to as a field. For each field, the treatment plan calculates the shape of the beam and the time duration the radiation beam should be applied. By applying radiation at several fields, with the shape of the beam optimized to account for the cross sectional shape of the tumor and other anatomical factors, a conformal dose is delivered. In general, the tracking of tumor movement described herein is the motion that occurs while executing the plan for a single field.

[0035] In an intensity modulated radiation therapy (IMRT), while each field is being executed, the multiple leaves in MLC beam adjuster 16 move so that different portions of the tumor cross-section receive different amounts of radiation. For example, if one part of the tumor is close to a critical or sensitive structure, the leaves in MLC beam adjuster 16 may

block the radiation near that part during some portion of the field, thereby decreasing the radiation dose receiving by that part of the tumor and minimizing the possible adverse effect of the radiation exposure by the critical or sensitive structure. When moving of the multiple leaves in MLC beam adjuster 16 to track the tumor movement in conjunction with an IMRT plan, the motion of the leaves to achieve IMRT will be superimposed on the motion of the leaves to track the tumor. In a standard IMRT treatment process, the IMRT motion is calculated for each field. In accordance with an embodiment of the present invention, it is generally sufficient to use the IMRT plan for a field calculated at some phase within a breathing cycle. Alternatively, a separate IMRT plan can be calculated for each of a plurality of phases in a breathing cycle in each field.

[0036] In accordance with another embodiment, the relationship between the tumor movement and the patient's breathing is established during treatment planning step 51. Such relationship can be obtained by imaging the tumor at various phases of the patient's breathing cycles. Techniques suitable for imaging the tumor at planning step 51 include planar radiography, ultrasound (US), computed tomography (CT), single photon emission computed tomography (SPECT), magnetic resonance imaging (MRI), magnetic resonance spectroscopy (MRS), positron emission tomography (PET), etc. The established relationship between the tumor movement and the patient's breathing facilitates the prediction of the tumor movement. In accordance with yet another embodiment, the relationship between the tumor movement and patient's thorax

and abdomen movement is established. The established treatment plan is stored in control module 18.

[0037] In a marking step 52, one or more fiducial markers having a known position relative to the tumor are provided. In accordance with one embodiment, the markers are implanted into the patient. Depending on the nature and location of the tumor, the fiducial markers may be implanted on the tumor or in the tissues surrounding the tumor. In another embodiment, fiducial markers are placed on the thorax and/or abdomen of the patient.

[0038] A fiducial marker can have various shapes, e.g., spherical, elongated cylindrical, etc. In accordance with one embodiment, a fiducial marker is a metal cylinder having a diameter ranging between approximately 0.5 millimeter (mm) and approximately 1 mm and a length ranging between approximately 2 mm and approximately 4 mm. In accordance another embodiment of the present invention, a fiducial marker has an asymmetric three-dimensional structure that enables the determination of its location and orientation through a single image. Fiducial markers having asymmetric structures are described in U.S. Patent Application Serial No. 09/178,383 entitled "METHOD AND SYSTEM FOR PREDICTIVE PHYSIOLOGICAL GATING OF RADIATION THERAPY" and filed on October 23, 1998, U.S. Patent Application Serial No. 09/712,724 entitled "METHOD AND SYSTEM FOR PREDICTIVE PHYSIOLOGICAL GATING OF RADIATION THERAPY" and filed on November 24, 2000, and U.S. Patent Application Serial No. 09/893,122 entitled "METHOD AND SYSTEM FOR PREDICTIVE PHYSIOLOGICAL GATING" and filed on June 26, 2001, which are incorporated herein by reference in their entireties.

[0039] The composition of the fiducial markers preferably has a stable chemical property that does not have significant reaction with the tissues surrounding the marker. The stable chemical property is especially preferred for internal markers to be implanted into the patient. Further, the composition of the fiducial markers is preferably substantially opaque to the image beam generated by image beam source 11, thereby forming a sharp image on image detector 17. Appropriate materials for the fiducial markers include, but are not limited to, gold, tungsten, tantalum, titanium, etc. The fiducial markers can also include a radioactive isotope material to enhance the image quality. The fiducial marker can also include paramagnetic or ferromagnetic materials to form magnetic markers or seeds.

[0040] After placing the patient on couch 14, the radiation treatment session starts in a start step 53 by activating control module 18 to execute the treatment plan. According the treatment plan, control module 18 generates signals to control the operations of image beam source 11, image detector 17, radiation source 12, beam adjuster 16, couch 14, and gantry 25.

[0041] In a step 54, image beam source 11 generates an image forming beam, e.g., a low energy X-ray radiation beam at the kV energy spectrum. The image forming beam illuminates at least a portion of the patient on couch 14 that includes the tumor under treatment and the surrounding area. The image forming beam penetrates the body of the patient and illuminates image detector 17 placed on the opposite side of the patient from image beam source 11. The fiducial markers

in the body of the patient partially block the image forming beam, forming images on image detector 17.

[0042] In a step 55, image detector 17 generates an image signal of the fiducial markers and transmits the signal to control module 18. Control module 18 processes the image signal and calculates the location, shape, and/or size of the tumor in the patient.

[0043] In an alternative embodiment, instead of being implanted into the patient, external markers are placed on the thorax and abdomen of the patient. In this embodiment, radiation therapy process 50 does not include step 54 of generating image forming beam. Further, image detector 17 includes a video camera, as described herein above with reference to Fig. 3, to generate image signals regarding the external markers on the patient. The movement of the tumor is deduced from the images of the external markers through the relationship there between established during treatment planning step 51. Process of deducing tumor positions from the images of external markers is described in U.S. Patent Applications Serial Nos. 09/178,383, 09/712,724, and 09/893,122, which have been incorporated in their entireties. Generally speaking, the methods and apparatuses for detecting target movement for the purpose of gating the radiation beam can also be used for tracking the tumor movement as described herein. Furthermore, the information about the target movement collected by such methods and apparatuses may be used for tracking the tumor movement, as well as for gating the radiation beam in conjunction with tracking to shut off the radiation beam under certain circumstances.

[0044] In another alternative embodiment, radiation therapy process 50 does not include marking step 52 or generating image forming beam step 54. In this embodiment, image detector 17 includes one or more video cameras to generate the image signals regarding external anatomical contour of the patient. The movement of the tumor is deduced from the images of the external anatomical contour through the relationship there between established during treatment planning step 51. In this embodiment, the external anatomical contour of the patient functions as markers to indicate the tumor movement inside the body of the patient.

[0045] In yet another alternative embodiment, magnetic seeds are implanted into the patient to serve as fiducial markers. Radiation therapy process 50 does not generating image forming beam step 54. Image detector 17 includes one or more magnetic field detectors or sensors to generate the image signals regarding the positions of the magnetic markers. The movement of the tumor is deduced from the images of the magnetic markers through the relationship there between established during treatment planning step 51.

[0046] In a step 56, control module 18 generates a beam adjustment signal in response to the calculated location, shape, and/or size of the tumor as well as the treatment plan. The beam adjustment signal is transmitted to beam adjuster 16 to adjust the position of a radiation beam that will be projected onto the patient from radiation source 12. In accordance with one embodiment of the present invention, control module 18 can also generate a control signal to move couch 14 to reposition the patient, thereby facilitating the focus of the radiation beam onto the tumor in the patient.

Repositioning the patient in a radiation therapy is described in U.S. Patent 6,279,579 entitled "METHOD AND SYSTEM FOR POSITIONING PATIENTS FOR MEDICAL TREATMENT PROCEDURES" filed on October 23, 1998 and issued on August 28, 2001, which is incorporated herein by reference in its entirety. In accordance with another embodiment of the present invention, control module 18 can further generate a control signal to move gantry 25, thereby changing the position of the radiation beam projected on the patient.

[0047] In a step 57, radiation source 12 is turned on to generate a radiation beam toward couch 14. The radiation beam is collimated and shaped by beam adjuster 16, resulting in a radiation beam irradiating a particular portion, i.e., tumor, of the patient on couch 14.

[0048] After radiation source 12 is turned on to irradiate the tumor in the patient, steps 54, 55, 56, and 57 repeat to continuously and dynamically adjust the direction, shape, size, and intensity of the radiation beam projected onto the patient according to the treatment plan and the calculated tumor location, shape, and/or size. Radiation source 12 remains active to continuously to generate the radiation beam, which is collimated and dynamically adjusted by beam adjuster 16 to from the radiation beam projected on the patient. The generation and adjustment of the radiation beam in response to the tumor movement continue until the treatment session ends in a step 58 when the total dose for the treatment session is reached.

[0049] A course of treatment for a patient generally includes a plurality of treatment sessions, each session generally having several fields. During each field, control module 18

tracks the movement of the tumor using the image signals generated by image detector 17 and dynamically adjusts the radiation beam projected on the patient through beam adjuster 16.

[0050] Radiation treatment process 50 in accordance with the present invention is not limited to being that described herein above. In an alternative embodiment, the relationship between tumor position and the internal anatomy of the patient is established in planning step 51 by such means as planar radiography, US, CT, SPECT, MRI, MRS, PET, etc. In step 55 of radiation treatment process 50, the internal anatomy, e.g., diaphragm movement, lung movement, gastric movement, intestinal movement, of the patient is tracked using image detector 17. Some of the internal anatomical movements, e.g., diaphragm movement, can be tracked without using fiducial markers. Control module 18 deduces the tumor position from the internal anatomy data and generates signal to adjust the radiation beam projected on the patient.

[0051] In accordance with one embodiment of the present invention, radiation treatment process 50 incorporates a physiology gating process as that described in U.S. Patent Applications Serial Nos. U.S. Patent Application Serial No. 09/178,383, 09/712,724, and 09/893,122, which have been incorporated in their entireties. Specifically, control module 18 may generate a signal to momentarily shut down radiation source 12 in response to the tumor moving in an abnormal pattern. When the tumor resumes its normal movement, e.g., the periodic movement associated with the breathing of the patient, permitting the projection of the radiation beam thereon with minimum exposure to the surrounding tissues,

control module 18 turns radiation source 12 back on. For example, sudden and involuntary moves of the patient, e.g., coughing, sneezing, muscle cramping, etc., during a field may move the tumor unpredictably, thereby triggering control module 18 to momentarily shut down radiation source 12. In accordance with various embodiments of the present invention, the gating process can be combined with adjusting the radiation beam through beam adjuster 16, repositioning the patient through moving couch 14, and/or adjusting radiation beam direction through moving gantry 25.

[0052] Gating can be used in conjunction with radiation beam tracking in other ways as well. In a typical gating process during normal breathing, the radiation beam is turned on while the tumor is in a portion of the cycle where there is little motion, and turned off for the rest of the cycle. In conjunction with tracking, the radiation beam can be gated off for a lesser portion of the breathing cycle. In accordance with one embodiment of the present invention, if one portion of the cycle has extremely complex tumor motion, rapid motion, or motion for which it is difficult to establish an accurate correlation with marker or anatomical motion, the radiation beam is gated off for that portion, but left on while tracking the motion during the rest of the cycle.

[0053] In accordance with one embodiment of the present invention, control module 18 uses the tracking signals to directly control beam adjuster 16 to shape the radiation beam. In other words, the tracking signals are superimposed on the treatment plan in the control of beam adjuster 16. In accordance with another embodiment, the treatment plan is converted to a lookup table that preferably has taken

variations in tumor location, shape, and/or size into consideration. The lookup table is stored in the memory of control module 18. In response to the image signals, control module 18 generates the tracking signals. Control module 18 then uses the tracking signals to parse the lookup table to select the appropriate entries in the lookup table to control beam adjuster 16.

[0054] The movement of the tumor may include translational motion and rotational motion. The shape of the tumor may also change. To accurately track all these movement and adjust the radiation beam to track the tumor movement may require control module 18 to have a high power signal processor and beam adjuster 16 to have a high resolution and a high degree of freedom in the adjusting the shape of the radiation beam. These requirements can increase the complexity and cost of apparatus 10, 20, or 30. Certain approximations may be made to strike a balance between accurately tracking the tumor movement and reducing the cost of manufacturing, operating, and maintaining apparatus 10, 20, or 30.

[0055] In one exemplified embodiment, the tumor is assumed to be substantially rigid and have no significant rotational motion. In this assumption, tracking the tumor requires only three translational coordinates. Because the shape and orientation of the tumor do not change, a single fiducial marker implanted on or near the tumor is sufficient to indicate the location of the tumor. Two image beams not parallel to each other and two corresponding image detectors can accurately track the position of the tumor.

[0056] If the movement of the tumor is substantially planar, there are only two degrees of freedom in the movement of the

tumor. In this situation, a single image beam is sufficient to track the movement of the tumor. The tracking accuracy may be improved by adjusting the image beam to be substantially perpendicular to the plane in which the tumor moves.

[0057] In another exemplified embodiment, the tumor is assumed to be substantially rigid, but can have both translational and rotational movements. In this assumption, tracking the tumor requires three translational coordinates and three rotational coordinates. Multiple fiducial markers may be implanted on or near the tumor to indicate both the location and orientation of the tumor. Alternatively, a signal marker with an asymmetric feature may provide sufficient information in certain cases. Two image beams not parallel to each other and two corresponding image detectors can accurately track the position and orientation of the tumor.

[0058] If the rotational motion of the tumor is substantially around an axis having a fixed orientation in space, two markers implanted on or near the tumor not aligned with the rotational axis of the tumor can provide sufficient information regarding the rotational motion of the tumor. In general, four markers implanted on or near the tumor and not coplanar with each other are sufficient in tracking both the translational and rotational motion of the tumor.

[0059] If the shape and size of the tumor also change, more markers may be needed. In certain situation where the markers are positioned closely to one another, the markers may be distinctive from each other so that they can easily be individually identified by control module 18. Further, more than two image beams may be required to accurately track the location, shape, and size of the tumor. Fiducial markers

having asymmetric three-dimensional structures may be beneficial in tracking the tumor movement with a high degree of freedom.

[0060] By now it should be appreciated that an apparatus and a method for irradiating a target have been provided. A radiation process in accordance with the present invention includes tracking the movement of the target and dynamically adjusting the radiation beam in response thereto. This will minimize the radiation exposure of the area surrounding the target. In accordance with one aspect of the present invention, the target to be irradiated is a tumor in a patient. Using the apparatus and the method of the present invention in a radiation therapy can minimize the radiation exposure of the healthy tissues surrounding the tumor under the radiation therapy. The radiation therapy performed in accordance with the present invention is advantageous over the physiology gating process in the sense that the radiation beam does not need to be switched off when the tumor moves during a field, or can be switched off for lesser portion of a breathing cycle. Thus, the radiation treatment process of the present invention is more efficient than that of physiology gating. The apparatus in accordance with the present invention can be easily obtained by upgrading a control module in an existing radiation treatment apparatus. Additional modifications may include mechanically coupling one or more image beam sources and/or one or more image detectors to the existing radiation treatment apparatus.

[0061] While specific embodiments of the present invention have been described herein above, they are not intended as a limitation on the scope of the present invention. The present

invention encompasses those modifications and variations of the described embodiments that are obvious to those skilled in the art. For example, the method of irradiating a target in accordance with the present invention is not limited to irradiating a tumor in a human patient. The method is equally applicable in veterinarian medical treatment of animals. In addition, the radiation process in accordance with the present invention may find applications in other areas such as, for example, agriculture product treatment, biological inspection, mechanical structure inspection, etc.